

# Guadalupe pluton–Mariposa Formation age relationships in the southern Sierran Foothills: Onset of Mesozoic subduction in northern California?

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Received 11 May 2009; revised 13 July 2009; accepted 18 August 2009; published 12 November 2009.

[1] We report a new  $153 \pm 2$  Ma SIMS U-Pb date for zircons from the hypabyssal Guadalupe pluton which crosscuts and contact metamorphoses upper crustal Mariposa slates in the southern Sierra. A  $\sim 950$  m thick section of dark metashales lies below sandstones from which clastic zircons were analyzed at  $152 \pm 2$  Ma. Assuming a compacted depositional rate of  $\sim 120$  m/Myr, accumulation of Mariposa volcanogenic sediments, which overlie previously stranded Middle Jurassic and older ophiolite + chert-argillite belts in the Sierran Foothills, began no later than  $\sim 160$  Ma. Correlative Oxfordian–Kimmeridgian strata of the Galice Formation occupy a similar position in the Klamath Mountains. We speculate that the Late Jurassic was a time of transition from (1) a mid-Paleozoic–Middle Jurassic interval of mainly but not exclusively strike-slip and episodic docking of oceanic terranes; (2) to transpressive plate underflow, producing calcalkaline igneous arc rocks  $\pm$  outboard blueschists at  $\sim 170$ – $150$  Ma, whose erosion promoted accumulation of the Mariposa–Galice overlap strata; (3) continued transpressive underflow attending  $\sim 200$  km left-lateral displacement of the Klamath salient relative to the Sierran arc at  $\sim 150$ – $140$  Ma and development of the apparent polar wander path cusps for North and South America; and (4) then nearly orthogonal mid and Late Cretaceous convergence commencing at  $\sim 125$ – $120$  Ma, during reversal in tangential motion of the Pacific plate. After  $\sim 120$  Ma, nearly head-on subduction involving minor dextral transpression gave rise to voluminous continent-building juvenile and recycled magmas of the Sierran arc, providing the erosional debris to the Great Valley fore arc and Franciscan trench.

**Citation:** Ernst, W. G., J. B. Saleeby, and C. A. Snow (2009), Guadalupe pluton–Mariposa Formation age relationships in the southern Sierran Foothills: Onset of Mesozoic subduction in northern California?, *J. Geophys. Res.*, *114*, B11204, doi:10.1029/2009JB006607.

## 1. Introduction

[2] Conducting new mapping and petrotectonic studies in medial belts of the Klamath Mountains and the southern Sierran Foothills, and building on the contributions of many earlier workers, *Ernst et al.* [2008] proposed a plate tectonic scenario that described important aspects of the mid-Paleozoic–Mesozoic crustal growth of northern California. Through Middle Jurassic time, largely oceanic terranes that formed seaward and ultimately were assembled in the Klamaths and the Sierran Foothills, consist chiefly of intensely imbricated mafic-ultramafic complexes and superjacent, fine-grained terrigenous strata derived from previously accreted continental margin belts [e.g., *Burchfiel and*

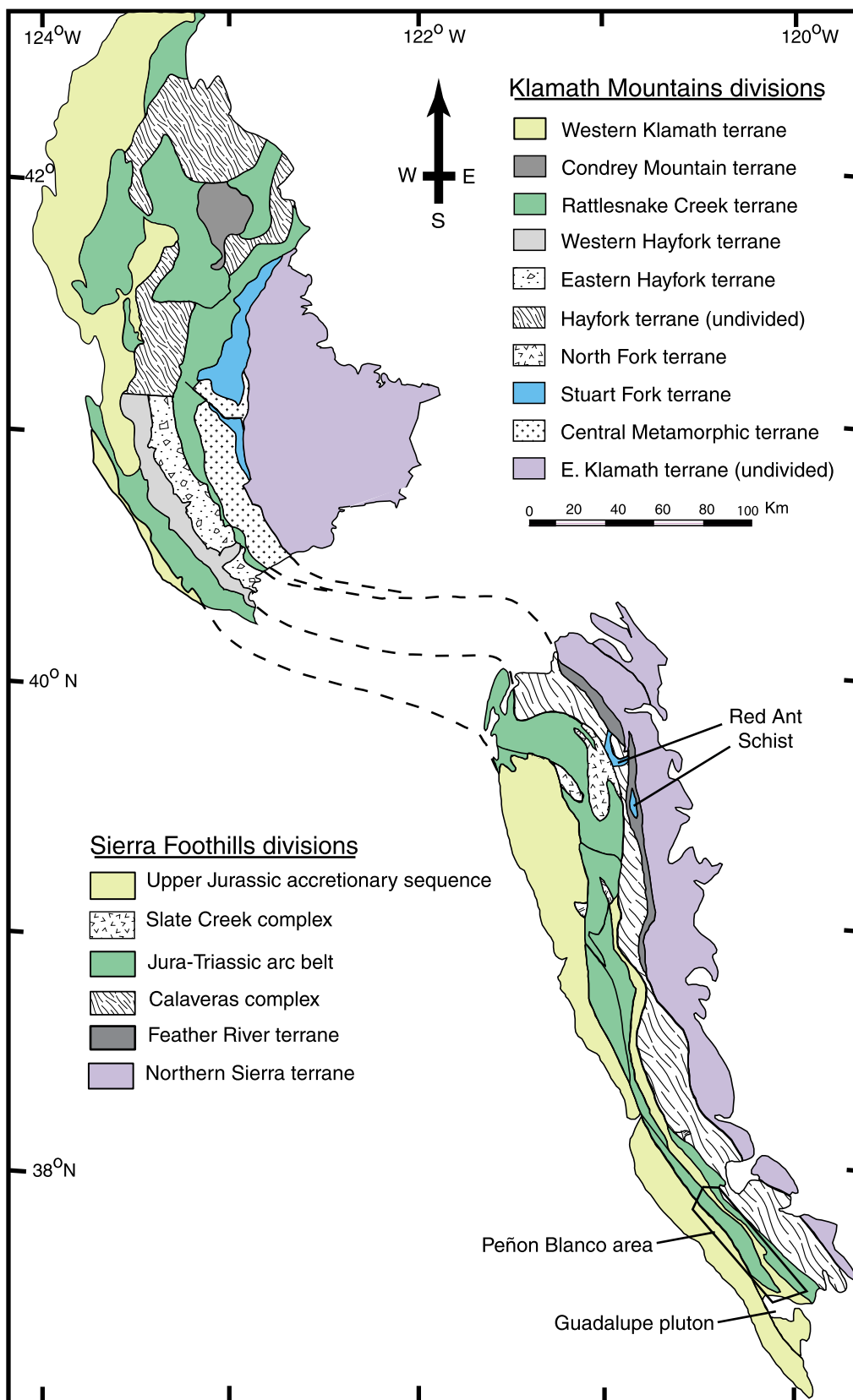
*Davis*, 1981; *Wright*, 1982; *Dickinson*, 2008; *Ingersoll*, 2008]. Although commonly regarded as products of convergent plate tectonic processes, sutured ophiolite + chert-argillite terranes apparently reflect  $\sim 230$  Myr of dominantly margin-parallel slip, involving minor stages of transtension and transpression [*Saleeby*, 1981, 1982, 1983; *Silberling et al.*, 1987; *Irwin*, 2003; *Ernst et al.*, 2008]. Felsic igneous units, quartzofeldspathic clastic rocks, and high-pressure metamorphic lithologies occur but are uncommon. The well-documented structural imbrication displayed by the Klamath–Sierran orogenic belt [e.g., *Irwin*, 1981; *Burchfiel and Davis*, 1981] requires an important component of convergence to account for the contraction, but the accretion of oceanic terranes argues for the dominance of continental margin parallel slip during assembly of the collage. Major terranes in northern California are shown schematically in Figure 1.

[3] In marked contrast, Late Jurassic–Early Cretaceous transpression, followed by the beginning of nearly head-on mid-Cretaceous subduction of the Farallon plate generated the massive Sierra Nevada volcanic-plutonic arc. It and the mineralogically immature Great Valley fore-arc and

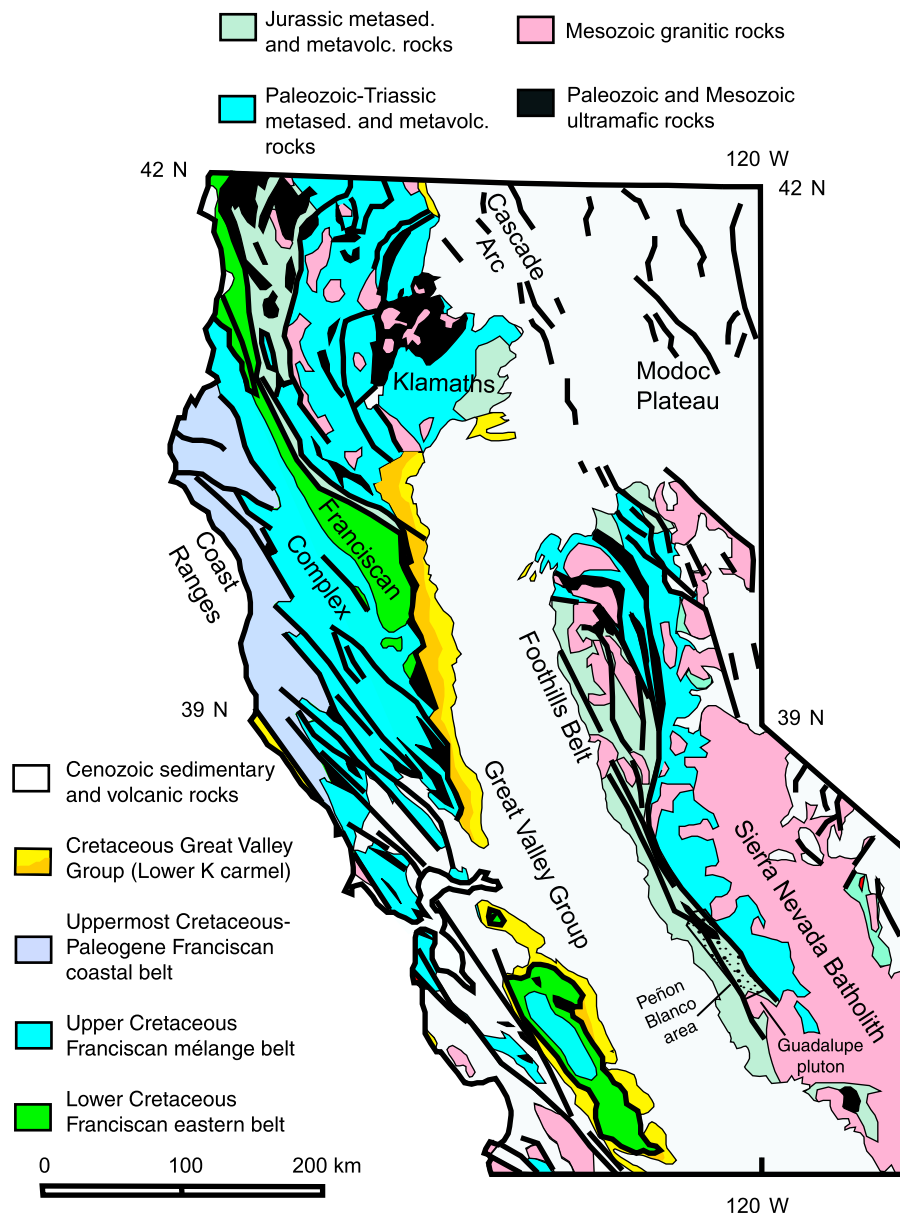
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**Figure 1.** Generalized geologic correlation map of the Klamath Mountains and the western Sierran Foothills, after Irwin [1981, 2003], Ando *et al.* [1983], Sharp [1988], Edelman and Sharp [1989], Ernst [1999], and Snow and Scherer [2006]. The Peñon Blanco map area of Snow and Ernst [2008] and the Guadalupe pluton are indicated. The Western Klamath terrane includes the Galice Formation, in the Sierran Foothills, the Upper Jurassic accretionary sequence includes the Mariposa Formation.



**Figure 2.** Geology of northern California, emphasizing the late Mesozoic calcalkaline arc, Great Valley fore-arc basin and Franciscan trench lithotectonic belts, generalized after the *U.S. Geological Survey and California Division of Mines and Geology* [1966] map, and the *Silberling et al.* [1987] terrane map. The study area of *Snow and Ernst* [2008] and the Guadalupe pluton are noted.

Franciscan trench deposits shed westward mainly from the parental Klamath-Sierran arc are illustrated in Figure 2. This triad of lithotectonic belts records ~70 Myr of rapid, subduction-induced growth of the sialic crust [Hamilton, 1969; Dickinson, 1970, 2008; Miller, 2004].

[4] The mid Jurassic apparently was a time of tectonic transition, involving major changes in plate motions and the onset of a substantial component of convergence. If the resultant calcalkaline arc and apron of derived volcanogenic sediments initially formed as a continuous curvilinear belt, this time interval evidently attended a progressive ~200 km outboard migration of the Klamath terrane amalgam relative to the Sierra Nevada [Ernst et al., 2008]. Initiation of volcanism-plutonism and the clastic detritus shed oceanward from the growing arc include Middle and Late Jurassic

granitoids [Stern et al., 1981; Bateman, 1992; Dunne et al., 1998; Dickinson, 2008] and their outboard erosional products such as the western Klamath Galice Formation [Harper et al., 1994; Miller and Saleeby, 1995; Gray, 2006] and the western Sierran Foothills Mariposa Formation [Sharp, 1988; Edelman and Sharp, 1989], both of Oxfordian-Kimmeridgian age. Dating the onset of construction of this Upper Jurassic sequence in terms of Mariposa sedimentation, based on macrofossils and microfossils reported by Imlay [1961], Clark [1964], and Graymer and Jones [1994], may well define the change from earlier, chiefly strike-slip plate motion to later transpression involving a major component of lithospheric convergence along the Californian sector of the North American margin.

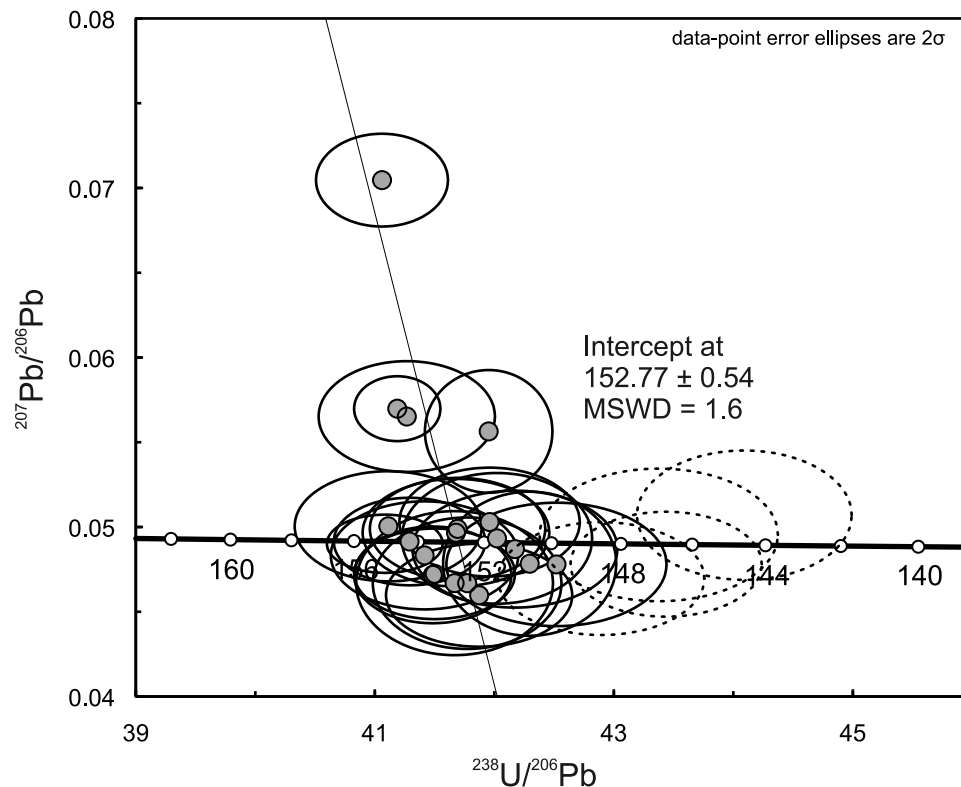
**Table 1.** Zircon U-Pb Analytical Data for Guadalupe Pluton, Sample G11<sup>a</sup>

		U	Th		Pb*	<sup>206</sup> Pb/ <sup>238</sup> U	<sup>207</sup> Pb/ <sup>206</sup> Pb	Discordance	Total <sup>238</sup> U/ <sup>206</sup> Pb
Analysis	Pb <sub>c</sub> (%)	(ppm)	(ppm)	Th/U	(ppm)	Age (Ma±1σ)	Age(Ma±1σ)	(%)	(±% Error)
G11-1	0.06	266	86	0.34	5.3	149.2 ± 2.1	42 ± 103.0	-72	42.67 ± 1.4
G11-2	0.22	361	148	0.42	7.2	146.6 ± 2.0	254 ± 70.0	72	43.37 ± 1.3
G11-3	0.98	1960	775	0.41	41.5	155.6 ± 1.7	178 ± 68.0	15	40.52 ± 1.1
G11-4	-0.27	394	138	0.36	8.0	151.4 ± 2.0	76 ± 68.0	-49	42.20 ± 1.3
G11-5	-0.16	482	182	0.39	10.0	153.3 ± 2.0	112 ± 85.0	-27	41.61 ± 1.3
G11-6	-0.15	513	194	0.39	10.3	149.3 ± 1.9	15 ± 76.0	-90	42.73 ± 1.3
G11-7	-0.16	340	158	0.48	7.0	152.5 ± 2.1	122 ± 72.0	-20	41.83 ± 1.4
G11-8	-0.11	440	172	0.40	9.3	156.5 ± 2.1	140 ± 63.0	-10	40.74 ± 1.3
G11-9	0.82	998	914	0.95	20.8	153.1 ± 1.8	196 ± 95.0	28	41.27 ± 1.2
G11-10	0.06	400	163	0.42	8.4	155.2 ± 2.0	112 ± 72.0	-28	41.00 ± 1.3
G11-11	0.15	438	168	0.40	9.1	154.1 ± 2.0	172 ± 65.0	12	41.28 ± 1.3
G11-12	-0.31	369	173	0.49	7.7	155.9 ± 2.1	-106 ± 117.0	-168	40.99 ± 1.3
G11-13	2.68	747	475	0.66	15.9	153.5 ± 1.8	-136 ± 225.0	-189	40.39 ± 1.2
G11-14	0.92	449	203	0.47	9.5	155.4 ± 2.0	222 ± 115.0	42	40.60 ± 1.3
G11-15	0.09	495	234	0.49	10.4	155.1 ± 2.0	131 ± 71.0	-16	41.01 ± 1.3
G11-16	-0.24	535	235	0.45	11.3	156.4 ± 2.0	45 ± 57.0	-71	40.83 ± 1.2
G11-17	-0.02	1346	883	0.68	28.6	157.6 ± 1.8	156 ± 33.0	-1	40.42 ± 1.2
G11-18	-0.40	442	218	0.51	9.2	155.2 ± 2.0	22 ± 64.0	-86	41.19 ± 1.3
G11-19	0.03	394	183	0.48	8.2	154.0 ± 2.0	188 ± 73.0	22	41.34 ± 1.3
G11-20	-0.31	369	174	0.49	7.7	155.5 ± 2.0	242 ± 121.0	55	41.09 ± 1.3
G11-21	-0.01	650	342	0.54	13.8	156.8 ± 1.9	170 ± 50.0	9	40.62 ± 1.2
G11-22	-0.05	353	125	0.37	7.3	153.6 ± 2.1	161 ± 67.0	5	41.49 ± 1.3
G11-23	0.11	411	200	0.50	8.7	157.3 ± 2.1	175 ± 64.0	11	40.44 ± 1.3
G11-24	-0.25	565	247	0.45	11.9	156.4 ± 1.9	76 ± 58.0	-51	40.81 ± 1.2
Analysis	Total <sup>207</sup> Pb/ <sup>206</sup> Pb(±% Error)	<sup>238</sup> U/ <sup>206</sup> Pb*(±% Error)	<sup>207</sup> Pb*/ <sup>206</sup> Pb- b*(±% Error)	<sup>207</sup> Pb*/ <sup>235</sup> U(±% Error)	<sup>206</sup> Pb*/ <sup>238</sup> U(±% Error)				
G11-1	0.0495 ± 3.2	42.81 ± 1.4	0.0469 ± 4.3	0.15 ± 4.5	0.0234 ± 1.4				
G11-2	0.0507 ± 3.1	43.34 ± 1.3	0.0513 ± 3.0	0.16 ± 3.3	0.0231 ± 1.3				
G11-3	0.0570 ± 1.4	40.89 ± 1.1	0.0496 ± 2.9	0.17 ± 3.1	0.0245 ± 1.1				
G11-4	0.0470 ± 2.9	42.17 ± 1.3	0.0475 ± 2.9	0.16 ± 3.2	0.0237 ± 1.3				
G11-5	0.0478 ± 3.6	41.59 ± 1.3	0.0483 ± 3.6	0.16 ± 3.8	0.0240 ± 1.3				
G11-6	0.0478 ± 2.6	42.81 ± 1.3	0.0463 ± 3.2	0.15 ± 3.4	0.0234 ± 1.3				
G11-7	0.0478 ± 3.1	41.79 ± 1.4	0.0485 ± 3.1	0.16 ± 3.4	0.0239 ± 1.4				
G11-8	0.0483 ± 2.7	40.72 ± 1.3	0.0488 ± 2.7	0.17 ± 3.0	0.0246 ± 1.3				
G11-9	0.0556 ± 2.7	41.56 ± 1.2	0.0500 ± 4.1	0.17 ± 4.3	0.0241 ± 1.2				
G11-10	0.0497 ± 2.6	41.07 ± 1.3	0.0483 ± 3.1	0.16 ± 3.3	0.0243 ± 1.3				
G11-11	0.0503 ± 2.6	41.32 ± 1.3	0.0495 ± 2.8	0.17 ± 3.1	0.0242 ± 1.3				
G11-12	0.0467 ± 3.7	41.12 ± 1.3	0.0441 ± 4.8	0.15 ± 4.9	0.0243 ± 1.3				
G11-13	0.0705 ± 1.6	41.79 ± 1.3	0.0436 ± 9.1	0.14 ± 9.2	0.0239 ± 1.3				
G11-14	0.0565 ± 2.4	40.90 ± 1.3	0.0506 ± 5.0	0.17 ± 5.1	0.0244 ± 1.3				
G11-15	0.0499 ± 2.5	41.08 ± 1.3	0.0486 ± 3.0	0.16 ± 3.3	0.0243 ± 1.3				
G11-16	0.0472 ± 2.3	40.84 ± 1.3	0.0469 ± 2.4	0.16 ± 2.7	0.0245 ± 1.3				
G11-17	0.0490 ± 1.4	40.41 ± 1.2	0.0492 ± 1.4	0.17 ± 1.8	0.0247 ± 1.2				
G11-18	0.0460 ± 2.7	41.17 ± 1.3	0.0465 ± 2.7	0.16 ± 3.0	0.0243 ± 1.3				
G11-19	0.0493 ± 3.2	41.31 ± 1.3	0.0498 ± 3.2	0.17 ± 3.4	0.0242 ± 1.3				
G11-20	0.0467 ± 3.4	40.87 ± 1.3	0.0510 ± 5.2	0.17 ± 5.4	0.0245 ± 1.3				
G11-21	0.0491 ± 2.1	40.60 ± 1.2	0.0495 ± 2.1	0.17 ± 2.5	0.0246 ± 1.2				
G11-22	0.0487 ± 2.9	41.46 ± 1.3	0.0493 ± 2.9	0.16 ± 3.2	0.0241 ± 1.3				
G11-23	0.0500 ± 2.7	40.47 ± 1.3	0.0496 ± 2.7	0.17 ± 3.0	0.0247 ± 1.3				
G11-24	0.0472 ± 2.5	40.79 ± 1.2	0.0475 ± 2.4	0.16 ± 2.7	0.0245 ± 1.2				

<sup>a</sup>Pb<sub>c</sub> and Pb\* are common and radiogenic lead, respectively; % is percentage of total.

[5] Using SIMS techniques, *Snow and Ernst* [2008] analyzed detrital zircons from Mariposa sandstone beds exposed in the Peñon Blanco area of the southern Sierran Foothills, and provided a geologic map locating the investigated specimens. The reported U-Pb maximum depositional age of  $152 \pm 2$  Ma is virtually identical to the previously published  $151 \pm 2$  Ma U-Pb TIMS age of magmatic zircons in the Guadalupe Igneous Complex obtained by *Saleeby et al.* [1989]. This pluton intrudes the Mariposa slates on the south [*Tobisch et al.*, 1989; *Haessler and Paterson*, 1993], so it is clear that one of these ages must be incorrect. *Snow and Ernst* [2008] separated and analyzed clastic zircons from sandstone layers situated >450

to 950 m above the unexposed base of the Mariposa Formation, so depending on the rate of deposition of black shales making up the lower part of the section, the detrital zircon ages reported by them could be considerably younger than the actual onset of sedimentation. Lying well below the lowest analyzed sandstone horizon, interstratified Logtown Ridge–Gopher Ridge volcanic rocks, the former apparently of Callovian age [*Graymer and Jones*, 1994], supports this idea. Alternatively, if the TIMS dating of the Guadalupe pluton involved the contribution of undetected old cores in the igneous zircons, the *Saleeby et al.* [1989] age of emplacement conceivably might be too old.



**Figure 3.** Tera-Wasserburg plot of analyzed zircons from specimen G11 of the Guadalupe pluton (SIMS data from Table 1). Several grains show minor apparent lead loss during cooling of the igneous body; this seems plausible based on the fact that the relatively mafic body solidified under conditions of roughly 800°C and 1 kbar  $P_{\text{fluid}}$  [Haeussler and Paterson, 1993].

[6] The present work reports new SIMS U-Pb age data that corroborate the *Saleeby et al.* [1989] time of crystallization of the Guadalupe pluton and reassigns an earlier beginning of deposition of the Mariposa muddy sediments through (1) comparison with analogous black shale deposition rates and (2) reassessment of the previously published Mariposa Formation detrital zircon ages.

## 2. Zircon U-Pb SIMS Age of Guadalupe Pluton Emplacement

### 2.1. Analytical Techniques

[7] We conducted single-grain core and rim analyses of purified zircons from Guadalupe specimen G11 using the Sensitive High-Resolution Ion Microprobe Reverse Geometry (SHRIMP-RG) instrument at the Stanford-USGS Micro-Analysis Center. Rock G11 and its zircon separates were previously described, and TIMS U-Pb ages reported by *Saleeby et al.* [1989]. In our work, ~40 grains were mounted and polished to about half original thickness, then imaged with both reflected light and cathodoluminescence. Igneous oscillatory zoning was detected in the subhedral to euhedral igneous zircons, but old cores were not recognized. Mounts were gold coated before analysis, and each grain was sputtered using a primary beam of  $\text{O}^{2-}$  ions with a spot size of ~25  $\mu\text{m}$ . Counts of  $\text{Zr}_2\text{O}$ ,  $^{204}\text{Pb}$ , background,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$ ,  $^{208}\text{Pb}$ ,  $^{238}\text{U}$ ,  $^{248}\text{ThO}$ , and  $^{254}\text{UO}$  were measured from the secondary beam. Zircons SL13 and CZ3 served as

concentration standards. Duplicate analyses of zircons R33 and CZ10 were employed for age corrections. We report ages calculated using the Squid data reduction program of *Ludwig* [2001]. All 24 analyses yielded ages far less than 1000 Ma; assuming an initial isotopic composition according to the Pb evolution curve by *Stacey and Kramers* [1975], we report  $^{206}\text{Pb}/^{238}\text{U}$  ages corrected by measured values of  $^{207}\text{Pb}$ . The analytical data are presented in Table 1. A concordia diagram was constructed using *Isoplot* [Ludwig, 2001].

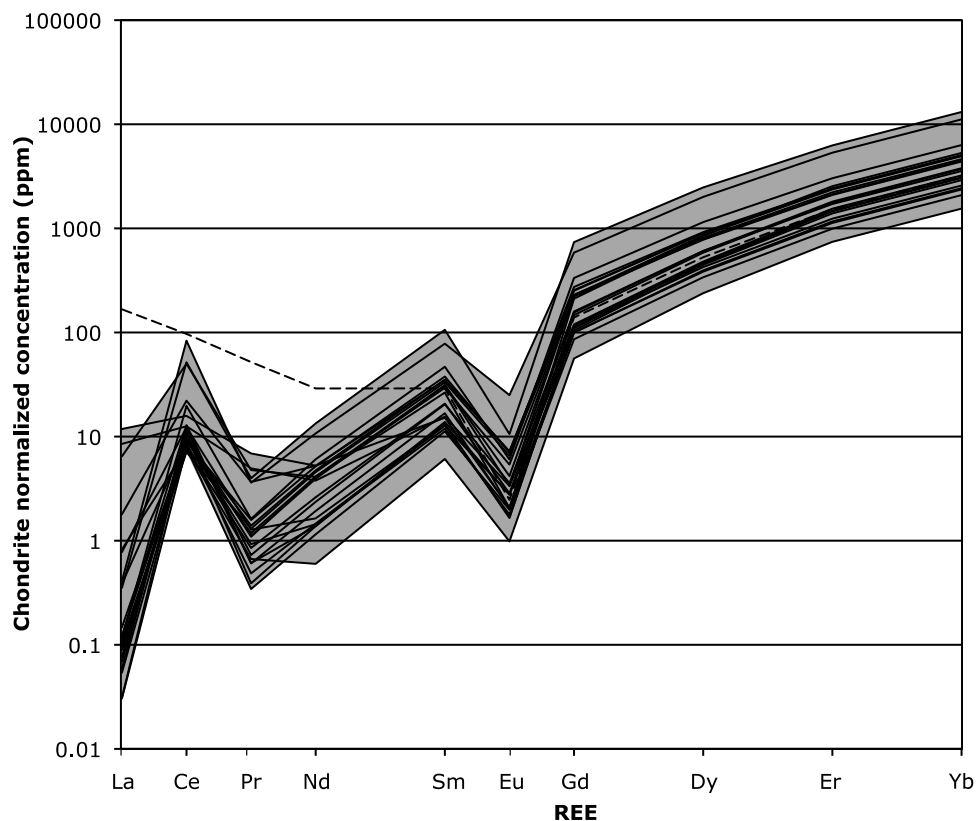
### 2.2. Results

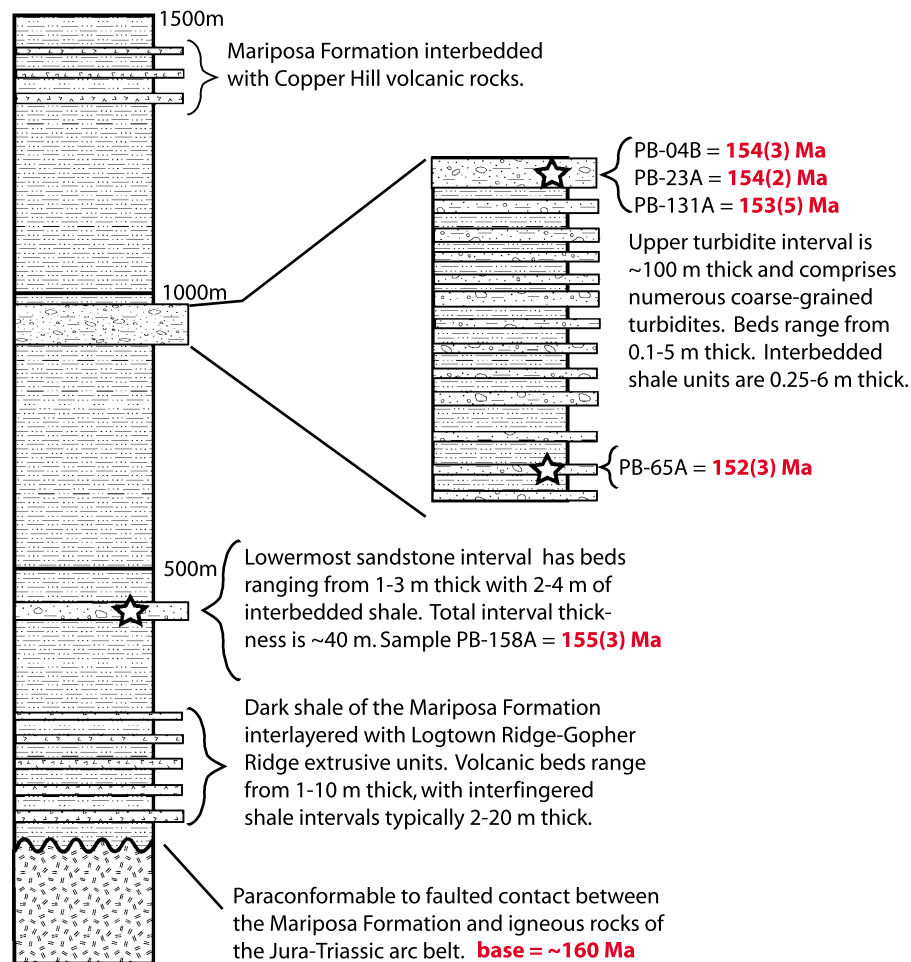
[8] A Tera-Wasserburg plot for the igneous zircons of sample G11 indicates that most of these 24 subhedral to euhedral grains are concordant within  $2\sigma$  uncertainty (Figure 3). The interpreted U-Pb age for this magmatic sample is  $153 \pm 2$  Ma, supporting the prior U-Pb zircon analysis by *Saleeby et al.* [1989]. If anything, our new SIMS age is slightly older than the TIMS age for the Guadalupe Igneous Complex.

[9] Zircon spot analyses from sample G11 exhibit an increasing trend of heavy REE ratios from La to Yb, which is characteristic of magmatic zircons (Table 2 and Figure 4). The pronounced peak in Ce is due to its compatibility in zircon relative to melt, especially at the relatively elevated oxidation states of the upper continental crust; moreover, remelted, preexisting sial would be rich in Ce because of the solubility of  $\text{Ce}^{+4}$  in aqueous solutions and consequent

**Table 2.** Zircon REE Analytical Data for Guadalupe Pluton, Sample G11

Sample	$^{206}\text{Pb}/^{238}\text{U}$ Age (Ma)	Chondrite Normalized Rare Earth Elements of Zircon									
		La	Ce	Pr (calc)	Nd	Sm	Eu	Gd	Dy	Er	Yb
G11-6	137	0.06	12.00	0.61	1.93	16.76	2.05	146.9	584.1	1765	3718
G11-11	142	0.07	11.53	0.73	2.36	20.46	3.57	155.4	605.6	1807	3784
G11-2	144	0.09	7.70	0.85	2.61	20.71	2.85	159.2	607.2	1715	3555
G11-12	146	0.10	8.13	1.19	4.13	29.42	5.38	222.2	788.2	2126	4473
G11-4	146	8.51	12.56	4.95	3.78	15.54	3.36	119.5	479.8	1546	3226
G11-15	147	0.78	12.30	1.28	1.64	12.97	1.67	112.1	425.0	1239	2579
G11-8	147	0.03	10.61	0.39	1.38	13.81	2.76	116.3	457.6	1458	3045
G11-1	148	0.82	7.64	0.67	0.60	6.09	0.98	56.3	238.4	743	1548
G11-24	148	167.0	96.9	52.0	29.00	29.04	2.47	139.3	528.1	1532	3214
G11-7	149	0.11	7.09	1.31	4.56	33.21	6.54	230.6	777.6	2095	4386
G11-20	149	0.03	7.81	0.34	1.15	11.22	1.98	86.1	339.2	994	2086
G11-19	149	11.83	15.80	6.89	5.25	15.19	2.07	100.5	384.0	1128	2364
G11-18	150	0.12	9.28	1.39	4.74	35.23	7.20	251.6	893.5	2411	5012
G11-23	151	0.15	8.92	1.58	5.18	37.72	6.99	273.7	920.4	2424	5053
G11-14	152	0.09	9.46	1.11	3.93	31.28	4.18	224.0	812.4	2218	4624
G11-22	152	0.38	9.28	0.93	1.44	11.93	1.78	99.5	394.5	1164	2430
G11-21	155	0.12	19.71	1.62	6.06	46.86	6.03	333.8	1148	3031	6314
G11-10	157	0.05	8.69	0.49	1.46	12.72	2.79	104.5	446.6	1393	2906
G11-16	158	0.08	10.31	1.09	4.12	31.00	3.36	227.7	857.6	2366	4938
G11-9	158	0.41	83.4	3.61	10.72	78.1	25.03	584.8	2005	5333	11140
G11-13	159	1.79	22.13	3.67	5.24	34.93	7.18	255.2	904.0	2407	5006
G11-5	159	0.12	12.88	0.61	1.38	13.26	1.65	109.5	472.3	1478	3095
G11-3	162	6.45	50.08	4.77	4.10	26.47	2.06	211.2	845.9	2542	5306
G11-17	169	0.35	51.74	3.98	13.38	106.1	10.58	737.6	2473	6265	13130

**Figure 4.** Rare earth element analyses of zircons from specimen G11 of the Guadalupe pluton (SIMS data from Table 2). The dashed curve represents a less reliable spot analysis that may have excited an undetected microinclusion contaminant such as epidote.



**Figure 5.** Stratigraphic column of the Mariposa Formation in the area surrounding the Cotton Creek anticline. Reconstruction of an exact stratigraphy was impossible due to limited outcrop control and extreme penetrative deformation [Bogen, 1984, 1985; Snow and Ernst, 2008]. Average ages of the 2–5 youngest detrital zircon grains from Snow and Ernst [2008] are shown in red.

long-term concentration in the sialic crust. The familiar negative anomaly in Eu in the zircons reflects the abundance of coexisting feldspar in the Guadalupe pluton.

### 3. Onset of Mariposa Deposition

#### 3.1. Regional Geology of the Upper Jurassic Accretionary Sequence

[10] The Mariposa Formation is the main member of the Upper Jurassic accretionary sequence exposed in the western Sierran Foothills. This superjacent unit occurs as a 250 km long NNW trending belt (Figure 1). On the south, Mariposa strata crop out along the flanks of the Cotton Creek anticline. As noted by Bogen [1984], it overlies the Peñon Blanco Formation (i.e., the Jura-Triassic arc belt, also called the Don Pedro terrane); the contact is locally a fault, as described below. In the area mapped by Snow and Ernst [2008], the Mariposa Formation comprises ~1.5–2 km of well-foliated black slate, 30–40 m of thick-bedded metaturbidites, and minor argillites [Bogen, 1984, 1985]. It exhibits the effects of pervasive deformation, with layering chiefly dipping steeply to the ENE [Best, 1963; Schweickert

et al., 1984, 1999; Haeussler and Paterson, 1993]. The formation was metamorphosed to subgreenschist grade and carries a neoblastic phase assemblage of quartz, albite, and chlorite ± epidote ± prehnite ± pumpellyite [Snow and Ernst, 2008]. Figure 5 presents the Mariposa stratigraphic column and sample sites for the Peñon Blanco section.

[11] Near its base, dominant black metashales ± argillites interfinger with Logtown Ridge–Gopher Ridge volcanic rocks on the western flank of the Cotton Creek anticline; these units are stratigraphically lower than the Mariposa Formation to the north in the Consumnes River area [Duffield and Sharp, 1975]. In contrast, the uppermost Mariposa appears to be intercalated with Copper Hill volcanic rocks southeast of the map area [Schweickert et al., 1999]. This latter unit is stratigraphically higher than the Logtown Ridge–Gopher Ridge volcanic rocks, indicating that Mariposa units exposed on the eastern side of the anticline are younger than strata cropping out on the western side of the fold. Furthermore, a NNW-SSE along-strike traverse on the east side of the Cotton Creek anticline reveals that lower Mariposa horizons are present near the nose of the structure, suggesting that different stratigraphic levels are in contact

with the underlying Peñon Blanco Formation. These same Mariposa strata lie below the upper turbidite interval on the east side, and the lowermost sandstones on the west side of the Cotton Creek anticline, establishing the relative stratigraphy presented in Figure 5. From these local relationships, *Snow and Ernst* [2008] concluded that the Mariposa–Peñon Blanco contact is a low-angle fault in the southern Sierran Foothills, although *Bogen* [1984] described it as paraconformable.

[12] Minor siltstone and sandstone lenses occur in the upper part of the Mariposa Formation; the coarser clastic beds are lenticular, range in thickness from 1 to 3 m, and fine upward from matrix-supported pebble conglomerate to medium-fine-grained siltstone; typically, they are separated by 2–4 m of black metashale. Approximately 30–40 m of feldspathic turbidites [*Bogen*, 1984] are interbedded with black slate over an interval of 100 m near the top of the section on the east side of the Cotton Creek anticline. Sandstone beds range in thickness from 0.1 to 5 m, and are separated by 0.25–6 m sections of thin-bedded black metashale. This distinctive section can be traced along strike for nearly 100 km, and is the coarsest clastic sediment in the Mariposa Formation. The turbidites exhibit SSE directed paleocurrent indicators [*Bogen*, 1984, 1985], suggesting that axial transport from the nearby Klamath-Sierran arc probably characterized the depobasin.

### 3.2. Detrital Zircon U-Pb Data and Onset of Mariposa Sedimentation

[13] Using SIMS techniques, *Snow and Ernst* [2008] analyzed zircon grains from five volcanogenic metaturbidites from different horizons of the Mariposa Formation. Mesozoic U-Pb age populations are dominated by zircons exhibiting a rather broad unimodal distribution from about 175–155 Ma. Here we are concerned with the beginning of Mariposa sedimentation, so emphasis is placed on the youngest detrital zircons in each sandstone bed. All of these units could have more recent ages of sedimentation than indicated by the youngest analyzed grains; the latter are a function of the nature of the then eroding source terrane and submarine distributary channels supplying the detritus. Nevertheless, investigating 5386 zircon U-Pb ages from 61 geologically geochronologically well-dated Colorado Plateau stratigraphic units, *Dickinson and Gehrels* [2008] used a variety of statistical techniques on low-discordance grains, and reported that the single youngest analyzed grain provides an accurate measure of the time of deposition in 95% of the rocks. In our study, in order to err on the conservative side, we averaged 2–5 of the youngest grain ages to arrive at the maximum age of sedimentation for a particular sandstone unit.

[14] Of the four stratigraphically higher metaturbidite layers, two contain several grains as young as  $152 \pm 2$  Ma, indicating maximum depositional ages of the Kimmeridgian–Tithonian time boundary [*Pessagno and Blome*, 1990; *Walker and Geissman*, 2009]. The other two samples lack Tithonian or younger grains, but contain abundant 155–160 Ma zircons. About 500 m down section, the stratigraphically lowest studied metaclastic rock, PB-158A, contains three young grains that average  $\sim 155 \pm 5$  Ma. The youngest analyzed grains in the four higher layers constrain the beginning of sedimentation of this upper part

of the Mariposa Formation to no older than 152 Ma, but these units are at least 950 m above the unexposed formational base. Thus, Mariposa sedimentation probably began during or slightly prior to the late Oxfordian–early Kimmeridgian ages reported by *Imlay* [1961] and *Clark* [1964], which these authors based on occurrence of the macrofossil, *Buchia concentrica*. The SIMS data for specimen PB-158A suggest that deposition of the lowest metasandstone horizon in the approximate middle of the formation probably began only a few million years before emplacement of the crosscutting Guadalupe Igneous Complex [*Saleeby et al.*, 1989].

[15] The time required to accumulate the lower >950 m of the Mariposa black shales±argillites may be estimated by comparison with depositional rates for similar lithologies, such as those of the Great Valley Group. *Ingersoll* [1979] reported overall GVG net accumulation rates of 181 m/Myr for clastic shelf sedimentation, and 208 m/Myr for clastic slope deposits (minor associated shales would have had lower compacted sedimentation rates than the silty and sandy turbidites that dominate the section). More appropriately, the Upper Cretaceous Dobbins Shale of the GVG is lithologically and positionally comparable to black shales ± argillites of the Mariposa Formation. The 80–150 m thick Dobbins Shale accumulated over a time span of  $\sim 4$  Myr. [*Williams*, 1997; *DeGraaff-Surpless et al.*, 2002], providing a compacted average sedimentation rate approaching 40 m/Myr. The >950 m section of black slates of the Mariposa Formation probably did not require 20 or 25 Myr for its deposition, but if we assume a relatively generous compacted accumulation rate of  $\sim 120$  m/Myr, sedimentation could well have started  $\sim 8$  Myr before the up-section sandstones formed. Accordingly, we estimate that Mariposa deposition began by  $\sim 160$  Ma, earliest Oxfordian time; inasmuch as the base of the section has been removed by faulting, the onset of Mariposa sedimentation could have been even earlier. Accumulation of the uppermost part of this unit seemingly was nearly synchronous with the Kimmeridgian intrusion of the Guadalupe pluton.

[16] Aggregate zircon U-Pb age populations for the five studied Mariposa metaturbidites suggest that the zircons were derived mainly from the Jurassic Klamath-Sierran orogenic belt, especially the mid-Paleozoic–mid-Mesozoic terrane collage, and the spatially associated younger (175–155 Ma) arc volcanic rocks and granitoids [*Snow and Ernst*, 2008]. This interpretation is compatible with Mariposa paleocurrent measurements that indicate an overall southerly transport direction [*Bogen*, 1985]. In the western Klamath Mountains, the volcanogenic, turbiditic Galice Formation represents the NW continuation of Mariposa-type lithologies [*Gray*, 2006; *MacDonald et al.*, 2006]. *Miller et al.* [2003] reported a 153 Ma depositional age for the Galice, but accumulation may have begun during the earliest Oxfordian,  $\sim 160$  Ma based on biostratigraphic data summarized by *Saleeby and Harper* [1993], and on the local interdigitation of Galice metaturbidites with pillow lavas of the subjacent 164–162 Ma Josephine ophiolite [*Harper*, 2006; *MacDonald et al.*, 2006]. Similar to the Mariposa Formation, the provenance of Galice sandstones evidently was a combination of both older seaward oceanic ophiolite and chert-argillite complexes,



and younger, landward, nearly coeval calcalkaline arc sequences [Snook, 1977; Frost et al., 2006].

#### 4. Depth of Intrusive Emplacement of the Guadalupe Pluton

[17] The southwestern gabbroic-dioritic basal section of the Guadalupe Igneous Complex intruded the Mariposa Formation and crystallized at shallow depth under conditions estimated by Haeussler and Paterson [1993] as about 800°C and 1 kbar  $P_{\text{fluid}}$ . Building on earlier petrologic-structural investigations by Best [1963], Tobisch et al. [1989], and Saleeby et al. [1989], Haeussler and Paterson demonstrated that ductile deformation of both pluton and surrounding Mariposa units occurred attending earliest Cretaceous reverse faulting along the Bear Mountains fault zone, which bounds the pluton along its SW border. This resulted in northeastward tilting and uplift of the igneous body and its adjacent wall rocks, preferentially exhuming the southwestern, more refractory portion of the pluton.

[18] The Mariposa section was strongly folded, shortened, and truncated by low-angle faulting, hence its stratigraphic or tectonic thickness attending intrusion of the Guadalupe mafic magma is poorly constrained in terms of igneous emplacement depth. The deformed Mariposa lithotectonic belt may well have extended to depths approaching or even exceeding 5 km prior to intrusion of the pluton. Lower amphibolite-facies contact metamorphism of the SW wall rocks is indicated by the local production of cordierite + andalusite ± sillimanite [Best, 1963; Tobisch et al., 1989; Haeussler and Paterson, 1993], an occurrence compatible with a shallow level, low- $P$ /high- $T$  environment for solidification of the Guadalupe pluton. In this active arc environment, deposition of higher stratigraphic horizons of Mariposa sandstone beds interlayered with the shaley section evidently continued until intrusion of this hypabyssal igneous body.

#### 5. Plate Tectonic Implications

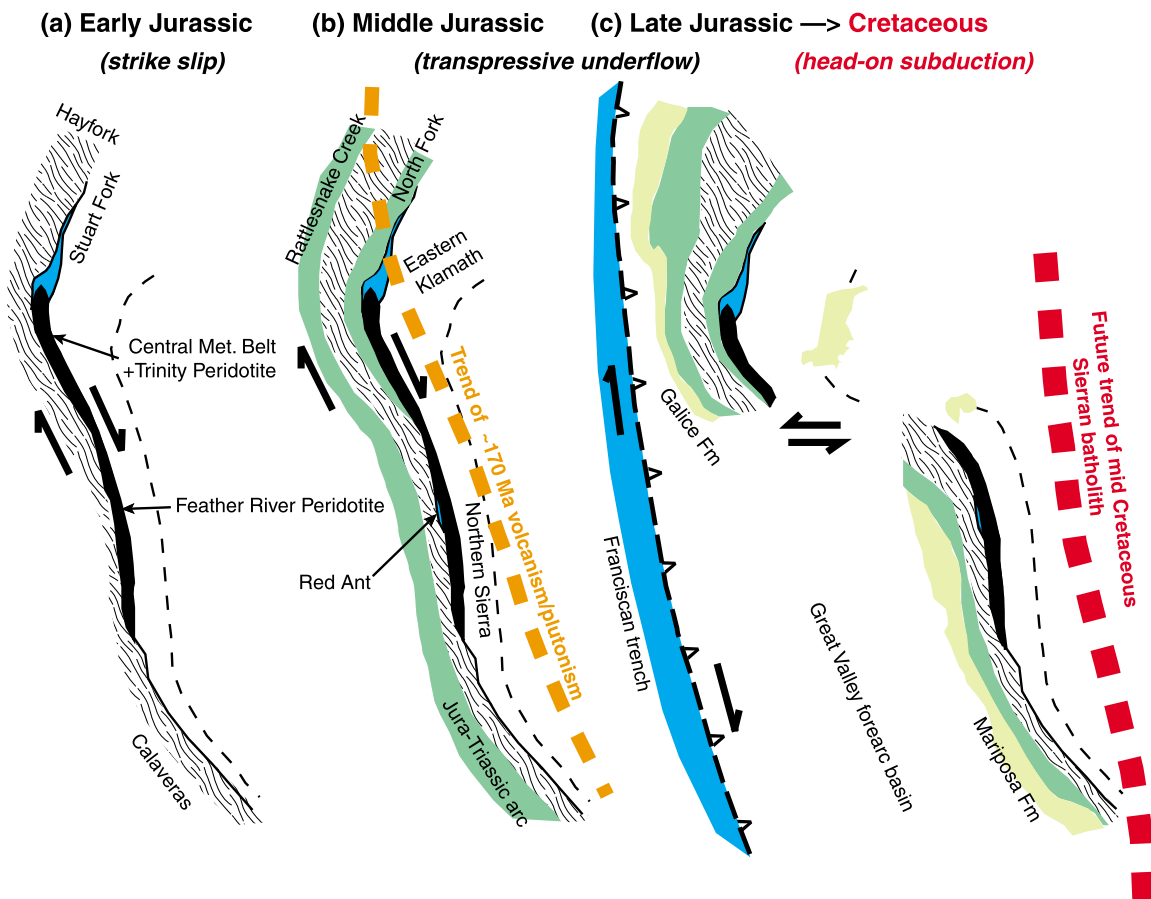
[19] A Middle Jurassic episode of calcalkaline volcanism-plutonism in the western Klamath Mountains and the Sierra Nevada and White-Inyo ranges, as well as fragmentary relics of the Red Ant blueschists in the northern Sierran Foothills [Stern et al., 1981; Wright and Fahan, 1988; Hacker and Goodge, 1990; Dunne et al., 1998; Ernst et al., 2002; Dickinson, 2008] suggest an important subduction component of transpression at ~170–150 Ma; nevertheless, dominant ophiolite + chert-argillite rock units were stranded along the edge of the continent due to largely conservative plate motions during the mid-Paleozoic–Middle Jurassic assembly of northern California [Saleeby, 1981, 1982, 1983; Silberling et al., 1987; Irwin, 2003]. The oceanic terrane collage was capped by terrigenous sediments and volcanics derived from an incipient arc; the latter must have started well before ~160 Ma, more likely ~170 Ma [Wright and Fahan, 1988; Dunne et al., 1998].

[20] At the end of Mariposa-Galice deposition, the Klamath salient was gradually displaced ~200 km to the west relative to the formerly contiguous Sierran arc [e.g., Coleman et al., 1988; Constenius et al., 2000; Dickinson, 2008]. The intrusion of ~170 Ma granitoid bodies in the

westernmost Klamaths and restricted occurrences of younger plutons to progressively more easterly belts [Hacker et al., 1995; Irwin and Wooden, 1999; Irwin, 2003] suggest that the left-lateral offset of the Klamath salient took place over the interval ~150–140 Ma as the crustal assembly of oceanic terranes and superjacent strata gradually migrated westward off the subducting plate's deep-seated magmatic zone. This seaward transport of the Klamath Province apparently occurred during a relatively brief period characterized by sinistral slip along the western margin of the continent [Saleeby, 1992; Saleeby et al., 1992], and terminated at the time of development of the Kimmeridgian-Tithonian cusp in the North and South American apparent polar wander paths [May and Butler, 1986; Schettino and Scotese, 2005]. The Guadalupe Igneous Complex itself exhibits the effects of sinistral shear.

[21] The Middle to Late Jurassic outboard generation of enigmatic high-pressure mafic amphibolites, blueschists, and eclogites [Coleman and Lanphere, 1971; Wakabayashi, 1990] now present as tectonic blocks in mélanges of the largely Cretaceous Franciscan Complex, as well as the onset of arc volcanism and the derivative Mariposa-Galice sediments, attest to establishment of an important component of convergence of the oceanic lithosphere beneath the Californian margin. High-pressure mafic tectonic inclusions formed in an oceanic transpression zone along an initially unrefrigerated, hot hanging wall (i.e., the mantle wedge), as evident from mineral parageneses that indicate counterclockwise  $P$ - $T$ -time trajectories [Wakabayashi, 1999; Anczkiewicz et al., 2004]. Current vectors and the fine-grained volcanogenic nature of clastic strata that make up the Mariposa-Galice sequences suggest their derivation from an emerging landward volcanic-plutonic arc [Bogen, 1984, 1985; Gray, 2006]. This mid-Jurassic change in plate motions probably involved oblique convergence rather than orthogonal subduction of the outboard oceanic lithosphere [Ernst et al., 2008]. Schematic geologic relationships for the Jurassic plate tectonic transitions in northern California are presented as Figure 6.

[22] In marked contrast, the calcalkaline flare-up of the arc became paroxysmal during mid Cretaceous time, when a major change from southward to northward tangential component of drift of the Pacific-Farallon plate occurred [Engelbreton et al., 1984; Sager, 2007]. T. A. Dumitru et al. (Early Cretaceous (circa 123 Ma) transition from nonaccretionary behavior to strongly accretionary behavior within the Franciscan subduction complex, submitted to *Tectonics*, 2009) have suggested that the convergent margin was transformed from a nonaccretionary to an accretionary margin at ~123 Ma. In any case, subsequent evolution of the continental margin involved the construction of three subparallel lithotectonic belts: (1) a massive Sierran batholith and its comagmatic but in-part earlier volcanic carapace [Stern et al., 1981; Bateman, 1992; Dunne et al., 1998; Irwin, 2003]; (2) a thick turbiditic section accumulating in the fore-arc basin as the Great Valley Group [Ingersoll, 1978, 1979, 1983; Linn et al., 1992; DeGraaff-Surpless et al., 2002; Surpless et al., 2006; Wright and Wyld, 2007]; and (3) the rapidly deposited graywackes and intercalated dark shales of the Franciscan Complex in the offshore trench [Bailey et al., 1964, 1970; Hamilton, 1969; Tripathy et al., 2005; Dumitru et al., 2007; Unruh et al., 2007; Snow



**Figure 6.** Diagrammatic scenario for mid Mesozoic evolution of northern California, assuming early, mainly dextral (?) strike slip of oceanic terranes along the continental margin, then a brief interval of margin-parallel left-lateral shear and end-of-Jurassic westward displacement of the Klamath oceanic arc, and finally by mid and Late Cretaceous subduction, modified from *Ernst et al.* [2008]. (a) Strike-slip suturing of the Eastern Hayfork–Calaveras amalgam at ~205–190 Ma. (b) Rifting of the Hayfork terrane at ~190–170 Ma and intra-arc spreading of the medial Klamath terrane assembly, with oceanic crust produced and/or tectonically inserted outboard (Rattlesnake Creek terrane and Jura-Triassic arc belt) and inboard (North Fork terrane), followed by onset of an important component of transpressive underflow, generating a Middle Jurassic calcalkaline belt with orange trend line of volcanic-plutonic arc from compilation by *Irwin* [2003] and outboard Red Ant blueschists. (c) Transpressive convergence resulting in hot hanging wall generation of high-grade amphibolites, blueschists, and eclogites at ~170–150 Ma, landward arc formation, and deposition of the Galice-Mariposa sequence, followed by westward step out of the transpressive plate junction, with sinistral migration of the Klamath salient relative to the along-strike Sierran arc attending the 150–140 Ma development of cusps in the North and South American apparent polar wander tracks [*May and Butler*, 1986; *Schettino and Scotese*, 2005]; continuing transpression created a modestly active volcanic-plutonic arc, fore-arc section, and trench deposits, giving way at ~125–120 Ma [*Sager*, 2007] to mid and Late Cretaceous nearly orthogonal subduction and production of the massive Sierra Nevada batholith, involving minor dextral transpression. The red dashed line is the trend of the mid Cretaceous batholith, after the compilation by *Irwin* [2003].

*et al.*, 2009]. The Sierran and Great Valley belts formed along the western margin of the North American plate, whereas the Franciscan was laid down on the approaching Farallon oceanic lithosphere. In northern California, the production of juvenile and reworked sialic crust was most voluminous in mid and Late Cretaceous time [*Stern et al.*, 1981; *Chen and Moore*, 1982], but erosional debris from the dying calcalkaline arc was supplied to the fore arc and trench into Paleogene time [*McLaughlin et al.*, 1982].

[23] Although orthogonal subduction may have only begun during mid Cretaceous time, an important change from mid-Paleozoic–Middle Jurassic dextral strike slip to transpression took place by ~170–160 Ma along the northern California margin, followed by a brief interval of left-lateral offset. Mid-Cretaceous and later head-on convergence involved at least a modest component of Late Cretaceous dextral transpression [*Engelbreton et al.*, 1984; *Nadin and Saleeby*, 2008], followed by Neogene overriding

of the East Pacific Rise [Atwater, 1970; Atwater and Stock, 1998], and a return to the modern transcurrent slip system. The subduction-generated massive volcanic-plutonic activity during mid and Late Cretaceous time produced an Andean calcalkaline arc directly east of the Sierran Foothills. The northern extension of the Late Cretaceous arc lay well to the east of the Klamath salient but has been covered by Cenozoic volcanic rocks of the Cascade and Modoc Plateau provinces.

## 6. Geochronologic-Geophysical Questions Posed by This Study

[24] 1. Presuming that the onset of Mariposa-Galilee deposition reflects a major change in Farallon–North American plate motions, from chiefly transform to transpressive involving a substantial component of convergence, better constraints regarding ages of the basal sedimentary units clearly are needed.

[25] 2. Did another major change in plate motion, from transpression to orthogonal subduction, occur at 125–120 Ma? If so, it must be more adequately defined and corroborated.

[26] 3. Processes responsible for the westward extrusion of the Klamath salient relative to the continental margin and more accurate timing of the progressive offset both require illumination.

[27] 4. Quantification of the amounts and directions of slip as a function of time is needed for each of the many imbricate contractional, extensional, and transcurrent faults transecting the Klamath-Sierran mountain belt.

[28] Riding passively on the underlying mantle substrate, these crustal units bear testimony to obscure deep-seated asthenospheric flow patterns. Consequently, all four tectonic problems noted above have their ultimate answers in a fuller understanding of the dynamic history and architecture of the upper mantle.

[29] **Acknowledgments.** Stanford University and the Geological Society of America Graduate Student Research Grant Program supported this research. Joe Wooden, Chris Mattinson, and Uwe Martens helped with the SHRIMP-RG analyses and data reduction. Marty Grove and Trevor Dumitru provided constructive feedback on a draft version of the manuscript. Ray Ingersoll and an anonymous reviewer gave us useful criticism for the journal article. We thank the above institutions and scientists for support and advice.

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